State of the art & future developments in the detection of nuclear/radioactive materials

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Overview

Definition of needs

State-of-the-art

Capability gaps

R&D requirements

The goal

The goal of detection measures is to reveal the presence of:

WHAT?

- **Radioactive Sources**
- **Special Nuclear Material**

WHERE?

- **Concealed in transports**
- **Borne by people**
- **Left in public places**

WHY? To prevent:

- **Preparation/use of an IND (crude nuclear weapon)**
- **Preparation/use of a RDD (dirty bomb)**
- **Contamination of public places, distribution networks, critical infrastructures,…**

Materials to be detected:

- **Fissile materials (U and Pu)**
- **Other radioactive materials**

Detection principle: radiation

Detectable types of radiation:

- **Photons**
- **Neutrons (Pu only)**

Detection principles

The ideal detector should have/be:

- **High sensitivity and efficiency**
- **Capability to discriminate the radiation source**
- **Easy to use (for non-experts)**
- **Reliable and able to work in harsh environmental conditions**

Detection principles

Radiation detection:

RS/SNM can be revealed by detecting the radiation they emit

Only exploitable radiation types: Photons / Neutrons

Main factors playing a role in radiation detection:

- **Amount and quality of radiation**
- **Properties of the sensor (efficiency/sensitivity/selectivity)**
- **Distance source/detector**
- **Exposure time**
- **Presence of radiation (background/natural/other sources)**
- **Presence of shields**

Efficiency (requirements)

High efficiency is required in order to maximise the probability that the detector "sees" the radiation:

- **Geometry effect:** **the larger is the detector surface, the larger will be the solid angle covered, so the probability that the radiation will reach the detector**

- **Interaction probability: proportional to thickness and density of the detection material**

Simplifying: efficiency increases with detector volume

Efficiency (state-of-the-art)

Current technology in radiation detection (efficiency):

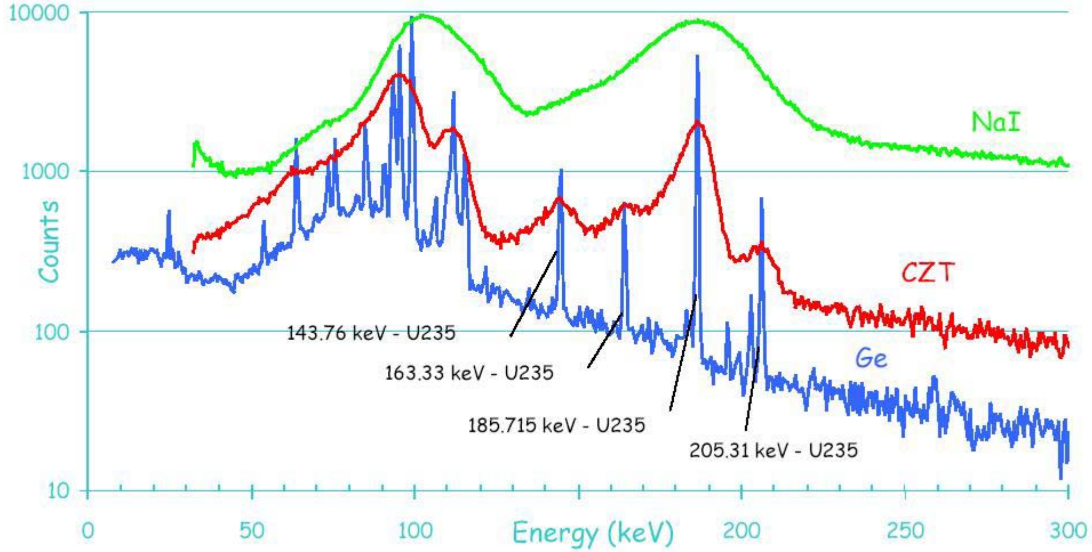
Detector family	Surface	Volume
Liquid scintillators	Any	Any
Plastic scintillators (PVT)	~10^4 cm^2	~10^1 l
Inorganic scintillators (NaI, $LaBr_3$,…)	~10^2 cm^2	~10^0 l
Semiconductors (HPGe,…)	~10^1 cm^2	~10^{-1} l

Resolution (requirement)

Resolution is required in order to discriminate and identify the material that has emitted the radiation

When a detector measures not only the presence of radiation (counting), but also is able to quantify the energy of the emitted photon (spectroscopy) it is possible to determine the isotope that has generated it

Resolution is the precision with which the photon energy is measured that determines the capability to isolate a characteristic peak in a spectrum



Resolution (state-of-the-art)

Current technology in radiation detection (resolution):

Detector family	Resolution	Capability
Liquid scintillators	No	No discrim.
Plastic scintillators (PVT)	Poor	Categorisation
Inorganic scintillators (NaI, $LaBr_3$,…)	Good	Simple spectra
Semiconductors (HPGe,…)	Excellent	Complex spectra

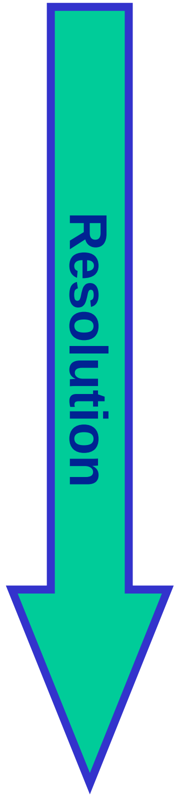
Detectors (state-of-the-art)

Liquid scintillators

Plastic scintillators (PVT)

Inorganic scintillators (NaI, $LaBr_3$,…)

Semiconductors (HPGe,…)



No perfect solution !

Detectors (state-of-the-art)

As a consequence a two-step procedure is applied:

I – Alarm triggered by a high efficiency fixed portal monitor (RPM)

II – Secondary inspection done by the front-line officer using portable equipment

Border monitoring

- **RPM: Radiation Portal Monitor installed at border checkpoints (road, rail, airport, seaport) to detect the presence of smuggled nuclear and other radioactive materials**

- **Their main requirement is a high efficiency: detect the presence of radioactive material in the short transit time**

Border monitoring

- **RPM are therefore based on material having the possibility to be built in large dimensions (plastic scintillators)**

- **The problem: Plastic scintillators have a high efficiency, but an extremely poor resolution. This means that it is not possible determine the energy of the radiation and therefore they cannot identify the isotope originating the radiation**

Radiation Portal Monitors

- Short measurement time requires a large sensor to achieve adequate statistics
- Broad range in vertical locations of potentially shielded sources dictates the need for a tall detector
- Must withstand extreme variation in ambient temperatures

- **Gamma detector**: Plastic scintillator (PVT)
  - high efficiency but low energy resolution
  - Large area coverage
  - Low cost
- **Neutron detector**

Radiation Portal Monitors

Strengths

- **Plastic scintillators can be made in relatively large size**
- **They have quite a large efficiency in gamma detection**
- **They can be integrated in the same case with ^{3}He neutron detectors**
- **They can detect small amounts of R/N material in a very short time**
- **They are not intrusive wrt vehicle throughput at border**
- **They are not very sensitive to environmental conditions**
- **Relatively cheap (wide market)**

BUT

Plastic scintillators have a poor resolution, so they cannot identify the material originating the radiation.

Types of alarm

- **False alarms:**

  alarms not triggered by the presence of any radioactive material inside the portal area (f.i. electronic noise)

- **Innocent alarms:**

  alarms produced by the justified presence of radioactive materials

  - **Naturally Occurring Radioactive Material**
  - **Medical isotopes**
  - **Legal shipments of radioactive sources**

- **Real alarms:**

  alarms produced by the unexpected (illegal?) presence of radioactive materials

Alarm rates

False alarm can be reduced by technical means.

IAEA recommends in technical specifications a requirement of false alarm rate <1/10000 events.

Innocent alarms depend on the frequency of NORM content in ordinary shipment or treated people in normal population.

Recent statistics report that approximately 1 to 2% of transits trigger an innocent alarm:

- several tens trucks per day in a border crossing station

- hundreds of containers per day in a port

needing secondary inspection

Innocent alarm rate

Alarms*	Reason	Max. observed multiple of background
10 per day	Industrial Products and Raw Material e.g. ceramics, fertiliser, lamps, TV, etc	10 / some events with e.g. ceramics
1 per week	Agricultural Products e.g. fruits, vegetable, wood, etc.	5 / e.g. one event with a chicken transport
1 per week	Iron and Metal Transports e.g. Scrap, etc.	50 / e.g. contaminated metal plates
1 per week	ADR (legal) Transport of Radionuclides e.g. radio pharmaceuticals and industrial sources, etc.	60 / almost all legal transports

* Traffic approximately 1000 trucks per day

Table 1: Categories of goods which triggered alarms at the ITRAP truck lane during an observation period of 6 months (totally about 200000 trucks)

WORLD CUSTOMS EXHIBITION AND FORUM, Budapest, 22-24th September 2003

Data source:

The Application of Gamma Spectrometric Techniques with Plastic Scintillators for the Suppression of "Innocent Alarms" in Border Monitoring for Nuclear and other Radioactive Materials

K. E. Duftschmid, Technical University Graz, Austria

Innocent alarm rate

Month	**Port of Antwerp**		
	Alarms/day	**Occupancies /day (truck)**	**Alarm rate**
Jan	108	10232	1.1%
Feb	118	10811	1.1%
Mar	148	11374	1.3%
Apr	144	11062	1.3%
May	165	13271	1.2%
Jun	156	11887	1.3%
Jul	195	14187	1.4%
Aug	***206***	15260	1.4%

NORM's

	K40	Th232	U238	Ra226
FOODS				
Brazil Nuts	100-500 Bq/kg			0-100 Bq/kg
Salt Substitute	>1500 Bq/kg			
Banana	100-500 Bq/kg			0-100 Bq/kg
Coffee	500-1000 Bq/kg			
Cereals	100-500 Bq/kg			
MATERIALS				
Granite	1000-1500 Bq/kg	100-500 Bq/kg		100-500 Bq/kg
Sand	100-500 Bq/kg	0-100 Bq/kg	0-100 Bq/kg	0-100 Bq/kg
Gravel	100-500 Bq/kg	0-100 Bq/kg		0-100 Bq/kg
Limestone	100-500 Bq/kg	0-100 Bq/kg	0-100 Bq/kg	0-100 Bq/kg
Concrete	500-1000 Bq/kg	100-500 Bq/kg		100-500 Bq/kg
Marble	100-500 Bq/kg	0-100 Bq/kg	0-100 Bq/kg	0-100 Bq/kg
Cement	100-500 Bq/kg	100-500 Bq/kg		100-500 Bq/kg
Brick	500-1000 Bq/kg	100-500 Bq/kg		500-1000 Bq/kg
Clinker	500-1000 Bq/kg	0-100 Bq/kg		100-500 Bq/kg
Coal fly ash	100-500 Bq/kg	0-100 Bq/kg		100-500 Bq/kg
Asbestos	100-500 Bq/kg	0-100 Bq/kg	0-100 Bq/kg	0-100 Bq/kg
Natural Gypsum	100-500 Bq/kg	0-100 Bq/kg	0-100 Bq/kg	0-100 Bq/kg
Pearlite	1000-1500 Bq/kg	0-100 Bq/kg	0-100 Bq/kg	0-100 Bq/kg
CERAMIC INDUSTRY				
Ceramic raw materials	500-1000 Bq/kg	0-100 Bq/kg	0-100 Bq/kg	
Ceramic Sludges	100-500 Bq/kg	0-100 Bq/kg	100-500 Bq/kg	
Zircon sands		500-1000 Bq/kg	>1500 Bq/kg	
White porcelain stoneware	500-1000 Bq/kg	0-100 Bq/kg	100-500 Bq/kg	
Ceramic tiles	500-1000 Bq/kg	0-100 Bq/kg	0-100 Bq/kg	
FERTILIZERS				
Phosphoric acid			1000-1500 Bq/kg	100-500 Bq/kg
Normal superphosphate	0-100 Bq/kg	0-100 Bq/kg	500-1000 Bq/kg	100-500 Bq/kg
Triple superphosphate	0-100 Bq/kg	0-100 Bq/kg	1000-1500 Bq/kg	100-500 Bq/kg
Mono ammonium phosphate	0-100 Bq/kg	0-100 Bq/kg	>1500 Bq/kg	0-100 Bq/kg
Di-ammonium phosphate	0-100 Bq/kg	0-100 Bq/kg	>1500 Bq/kg	100-500 Bq/kg
Di-calcium phosphate	0-100 Bq/kg	0-100 Bq/kg		500-1000 Bq/kg
NPK (nitrogen/phosphate/potassium)	0-100 Bq/kg	0-100 Bq/kg	100-500 Bq/kg	100-500 Bq/kg
PK (phosphate/potassium)	0-100 Bq/kg	0-100 Bq/kg	100-500 Bq/kg	100-500 Bq/kg
Phosphogypsum		0-100 Bq/kg	0-100 Bq/kg	100-500 Bq/kg
COMMERCIAL ITEMS				
Gas Lantern Mantle		500-1000 Bq/kg		
Tobacco				0-100 Bq/kg
Kitty Litter	100-500 Bq/kg	0-100 Bq/kg	100-500 Bq/kg	
Glossy paper (kaolin)		0-100 Bq/kg	0-100 Bq/kg	
Glazed Ceramics Surfaces		500-1000 Bq/kg	500-1000 Bq/kg	
NBS Glass		>1500 Bq/kg		

LEGEND

white	0 Bq/kg
light yellow	0-100 Bq/kg
yellow	100-500 Bq/kg
orange	500-1000 Bq/kg
red-orange	1000-1500 Bq/kg
brown	>1500 Bq/kg

Medical/industrial isotopes

	Am241	Ba133	Cs137	Co57	Co60	Ga67	I131	In111	Ir192	Tc99m	Ti201
HELTH & MEDECINE											
Medical Isotopes			X	X		X	X	X		X	X
Brachytherapy			X		X		X	X			
INDUSTRIAL ITEMS											
Smoke Detector	X										
Fluorescent Lamp starter					X						
Electronic Equipment		X									
Voltage Regulator			X								
Thickness Gauging Device			X								
Glow Lamp					X						
Moisture Density Gauge	X		X								
Radiography Camera									X		
Gamma Radiography					X			X			

Innocent alarm rate

Consequence of too high alarm rates:

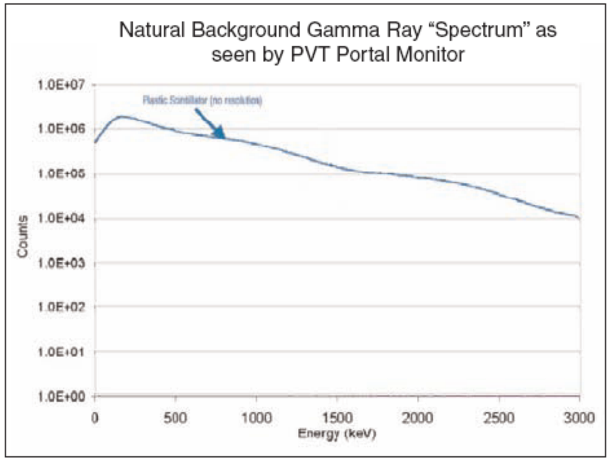
- **Overwhelming operational effort to be devoted to secondary inspections by FLO's**

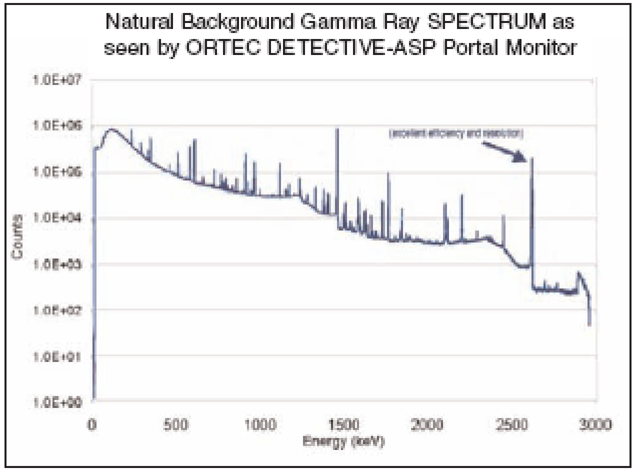
- **Inurement: FLO's gets used to see them and lower their attention level**

Need to tackle seriously the problem of alarm reduction

How to reduce innocent alarms ?

- **Secondary screening** to determine the specific source of alarming events could be done using a **spectroscopic portal monitor** of comparable detection sensitivity than PVT
  - But their cost is very high!
    (to purchase, to use & to maintain)





- **Spectral energy discrimination** could be used to control the nuisance alarm
  - Expertise required!

How to reduce innocent alarms ?

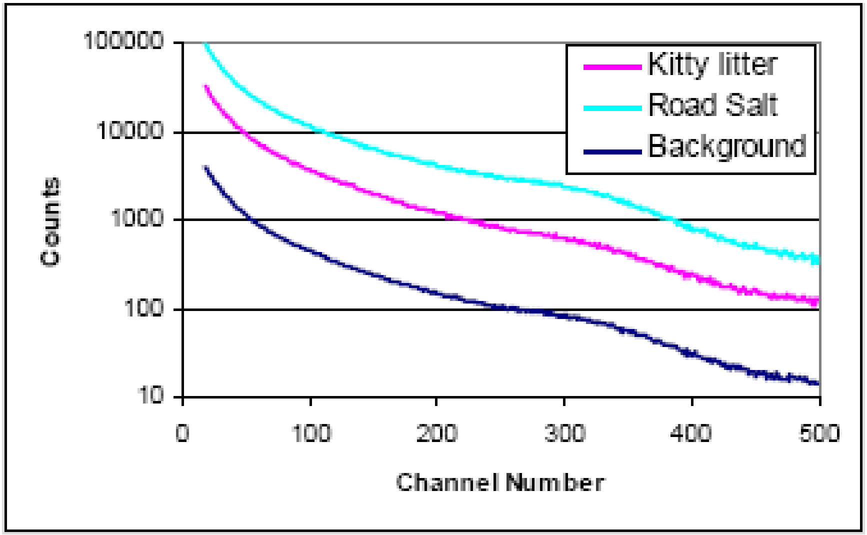
- Discrimination between **NORMs** **&** **SNM** **&** **Radioactive sources** is not straightforward. The **poor energy resolution** of the RPM does not allow isotope identification, and its response is poorly correlated in energy.

- But if PVT distorts the incident spectra, there are subtle variations in the energy response that allow spectral analysis by selecting a few broad energy windows. Discrimination between these 3 categories can be made via a broad energy windowing:
  - **Low energy window** = medical and SNM
  - **Medium energy window** = industrial isotopes
  - **High energy window** = NORMs

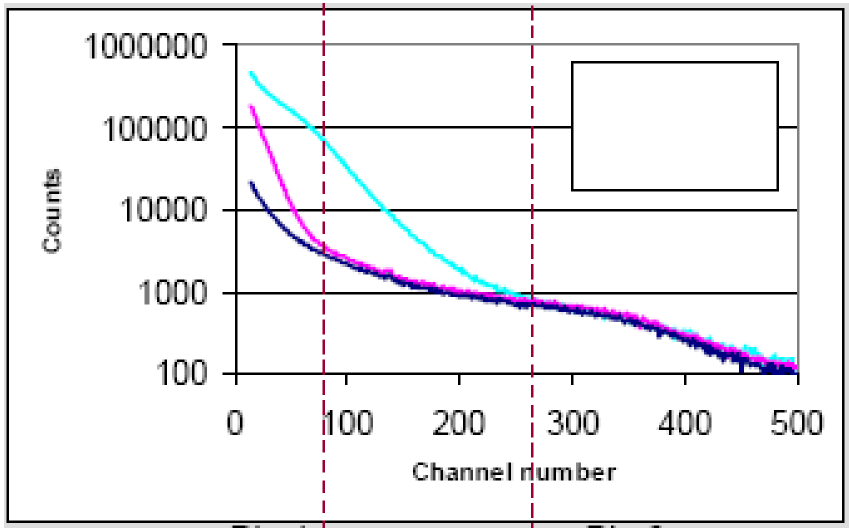
- Another way of discriminating NORMs would be to do a **secondary screening** to determine the specific source of alarming events. This could be done using a **NaI or a HPGe portal monitor** of comparable detection sensitivity than PVT.

Broad Energy Windowing Method

NORMs

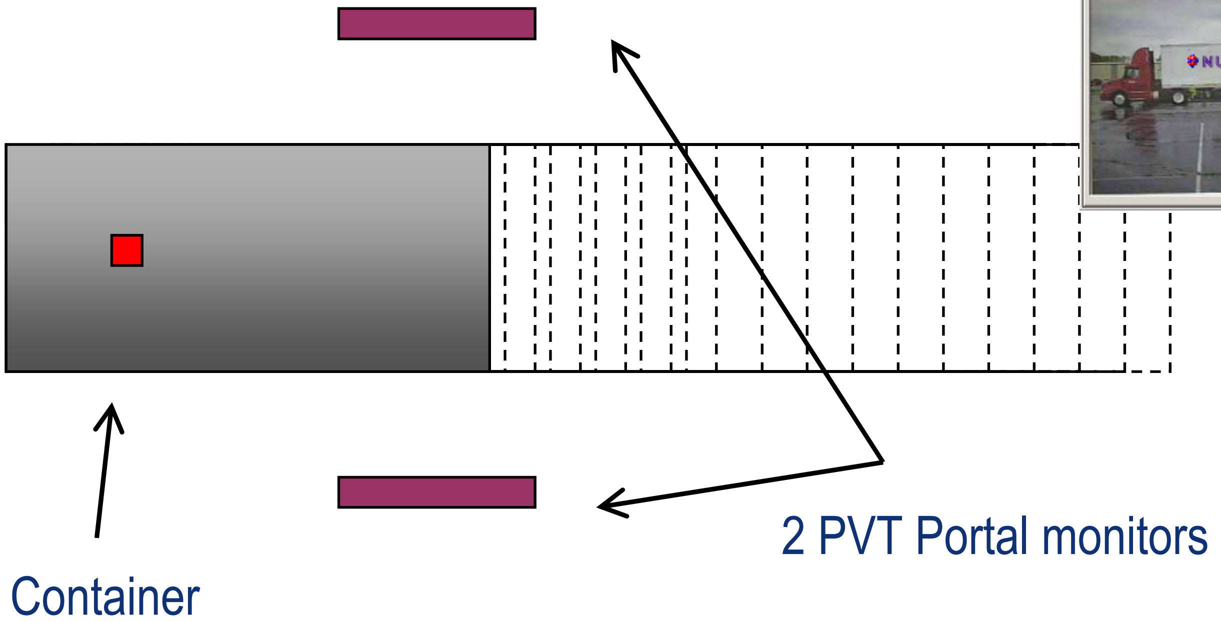


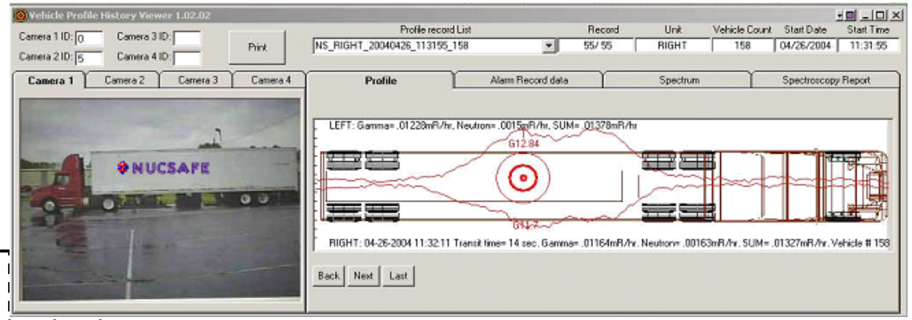
SNM



“Spies, lies and nuclear threat”, J.Ely & R.Kouzes, HPS, July 2005 meeting

- **If the alarm threshold of the total count rate is exceeded, the total counts are compared to the counts in the three energy windows**
  - **SNM will only trigger an alarm in the low energy window**,
  - **Industrial isotopes will trigger in the low & medium energy windows**
  - **NORMs will trigger an alarm in all the 3 energy windows (increase of the background level but the shape is the same)**



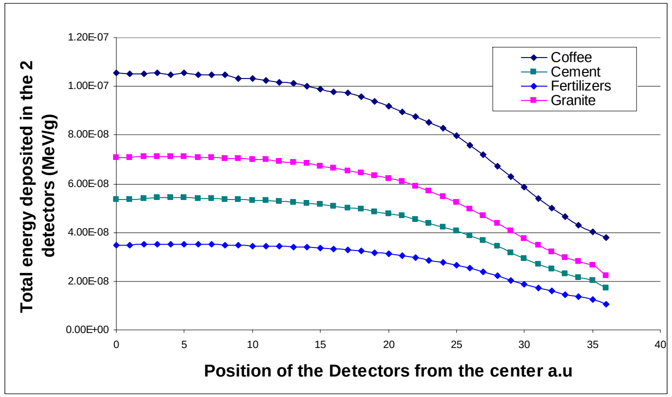


The total energy deposited in the portal monitors is calculated for each position of the truck moving forward

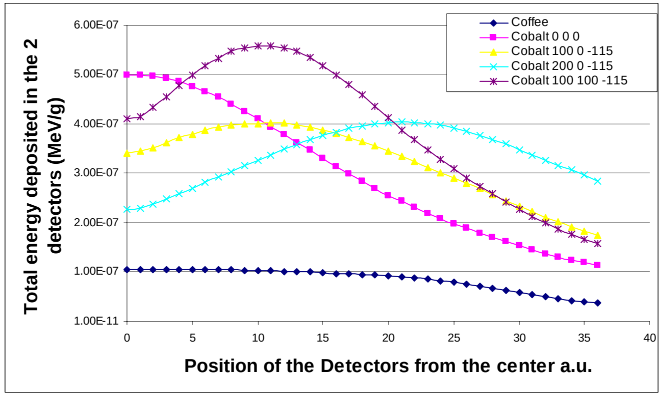
When containing **NORMs** the container is **homogeneously distributed**

When containing **SNM or a radioactive source**, the material is **locally positioned**

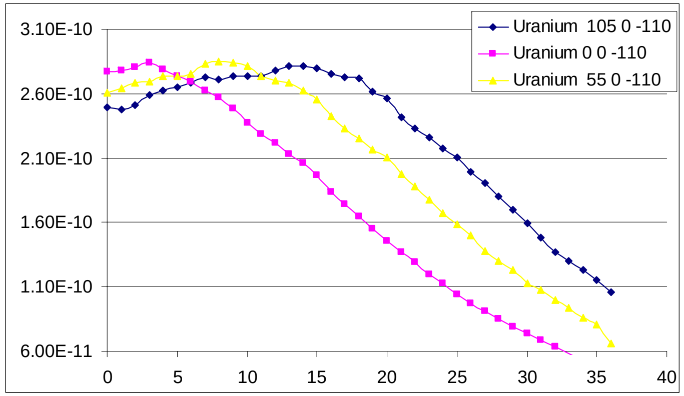
Discrimination with Spatial Distribution



NORM



1.7 g of Co-60



25 kg of HEU

- A **small radioactive source** will lead to a **narrow peak** of the detector response, while a homogeneous **NORM** container will lead to a **broader distribution**
- The full width at half maximum **(FWHM)** of the fitted gaussian will discriminate the distributed NORMs from the small and localized sources
- The space distribution will be obtained by coupling the time evolution of the detector response with a **truck speed detector**

Information analysis

Information analysis can help to improve the situation

For instance if:

- **Shipper declaration states a material typically containing NORM**
- **Broad energy windowing shows homogeneous increase in the spectrum**
- **Spatial profile confirms broad distribution**

=> then the material can be trusted to be NORM

There is much more information available than simple radiation level

Spectroscopic portal monitors

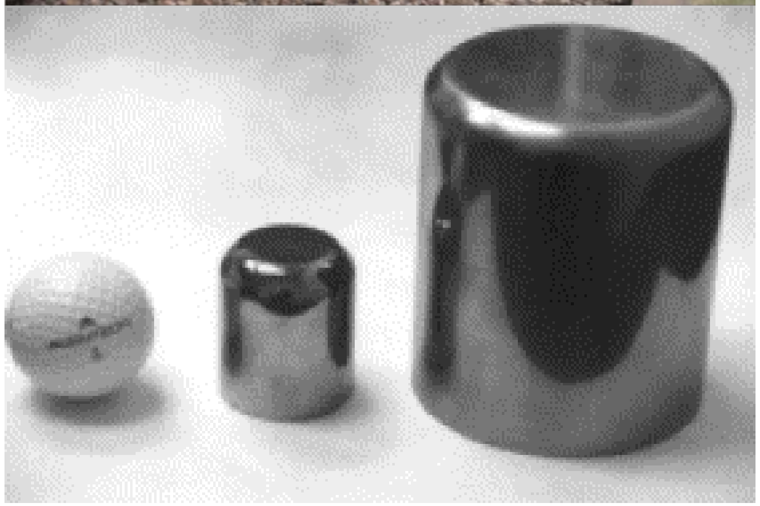
Spectroscopic portal monitors

- new generation of portal monitors under development
- combination of detection and nuclide identification provides the possibility to immediately identify NORM, medical as well as legal radioisotopes and to dramatically reduce innocent alarms
- complex system of detection modules and sophisticated software requires extensive testing
- can be applied in principle for trains, trucks, cargo, pedestrians
- spectroscopic portals provide an interesting option for future installations, however, they have higher resource requirements

- High resolution
- High sensitivity (results in a short time)
- Require cooling to low temperatures (LN2)
- High price
- Complexity of data treatment

Spectroscopic portal monitors

- Portal monitors have to cover a certain height for an efficient detection
- For constructional reasons, HPGe (and CZT) detectors cannot be produced in larger dimensions
- Largest HPGe detector[1]:
  - Ø 98 mm, length 110 mm
  - volume 110 cm^3, weight ≈ 4.4kg
  - at 3700 V operating voltage FWHM at 1.33 MeV: 2.4 keV

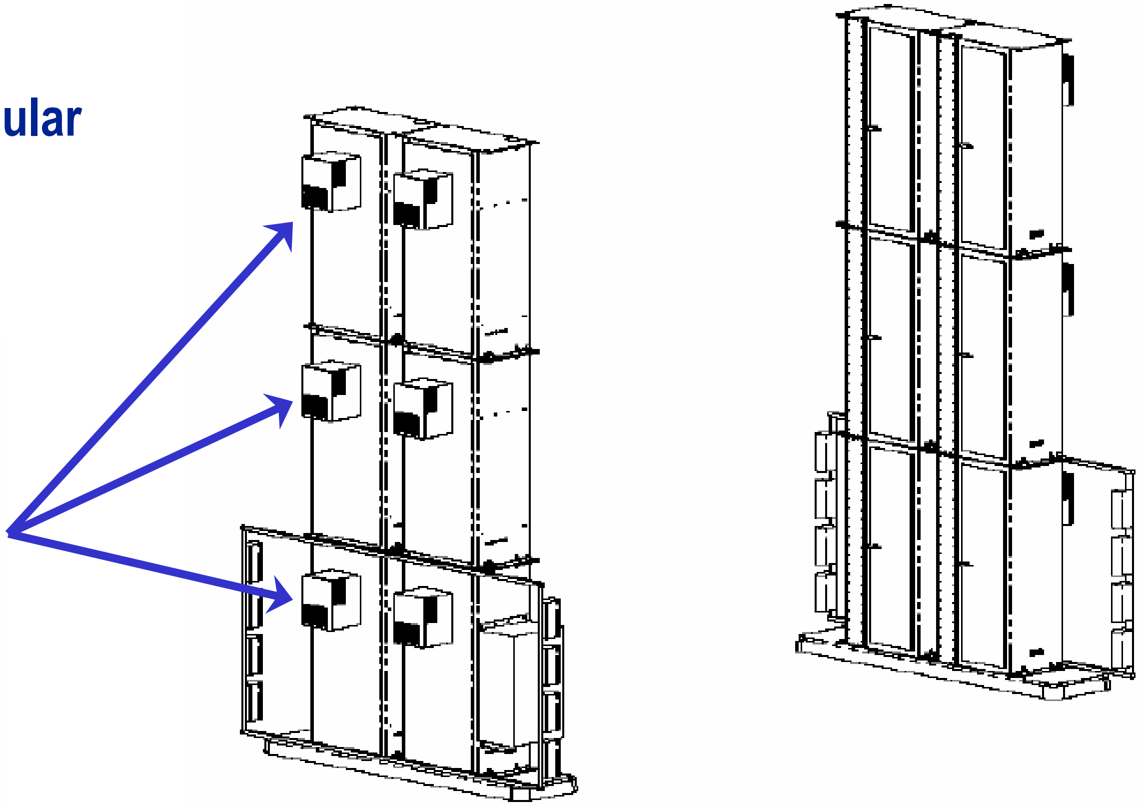


A portal monitor with one huge HPGe crystal cannot be achieved.

[1]Pat Sangsingkeow, Kevin D. Berry, Edward J. Dumas, Thomas W. Raudorf and Teresa A. Underwood, Advances in germanium detector technology, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Vol. 505, Issues 1-2, Proceedings of the tenth Symposium on Radiation Measurements and Applications, 1 June 2003, Pages 183-186. (http://www.sciencedirect.com/science/article/B6TJM-486229H-S/2/3b44eddbf14af13117b8a8d69947263c)

Spectroscopic portal monitors

Spectroscopic portal monitors can be constructed by combining several modular HPGe detectors

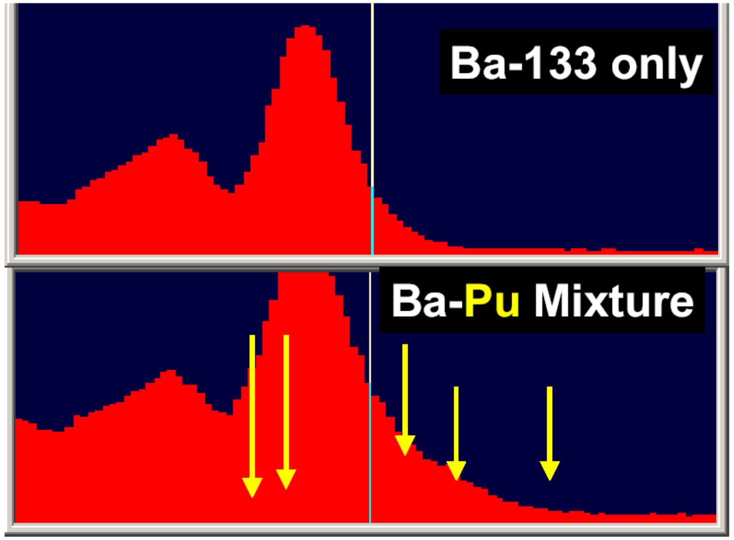


Modular electrically cooled HPGe detector with built-in ADC and USB connection (Ortec)

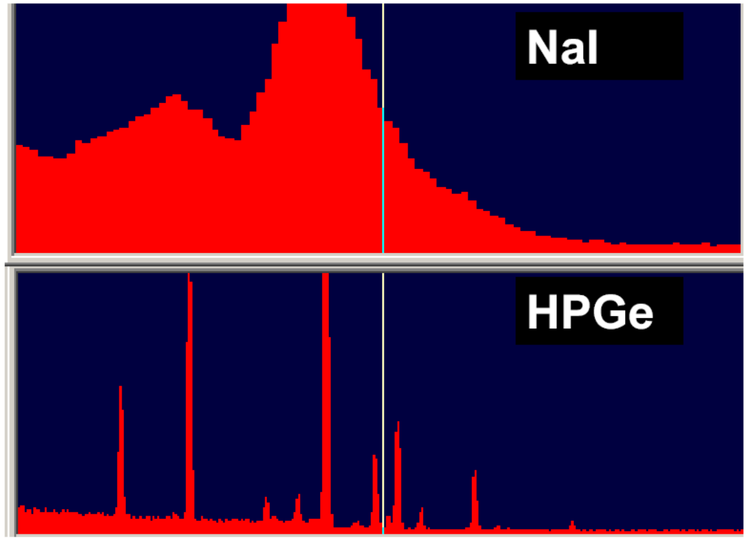
- Self-contained subsystem, comprising a single, electrically cooled HPGe detector of standardized crystal dimensions and all necessary electronics.
- Detects gamma rays and sends the energy histogram or digitized pulse stream directly to a PC for analysis.

Fissile hidden in declared RM

NaI Detector *(arrows indicate undetected Pu peaks)*



Weapons Grade Pu and Ba133 mixture



Spectroscopy can improve the capability to detect illegal material inside legal shipments of radioactive sources

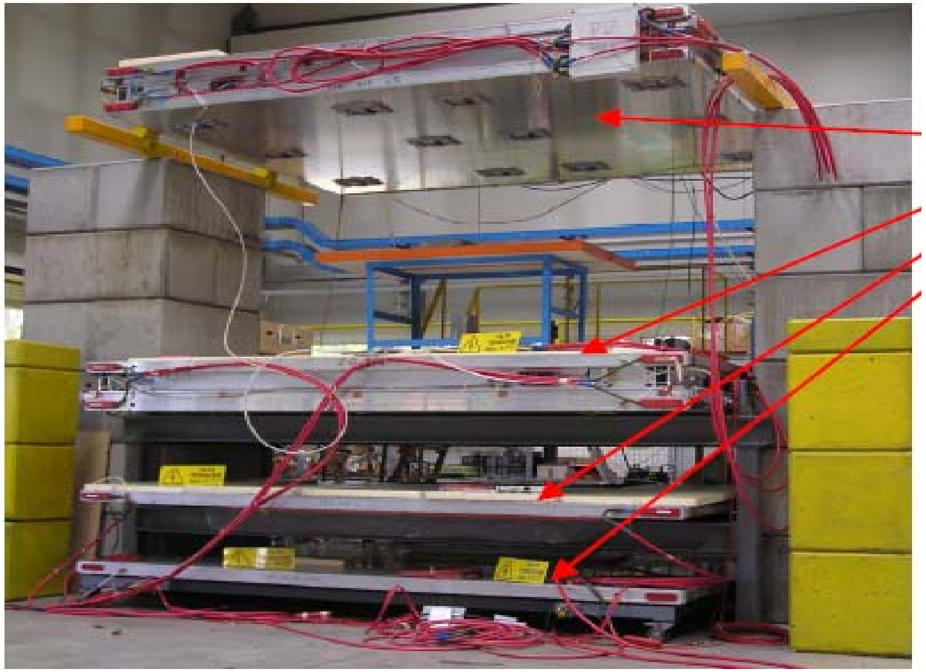
Detection of shielded material

Muon radiography to detect high-Z material:

- Direct detection of fissile material (U, Pu)
- Indirect detection of materials (Pb, W) used to shield RS/SNM

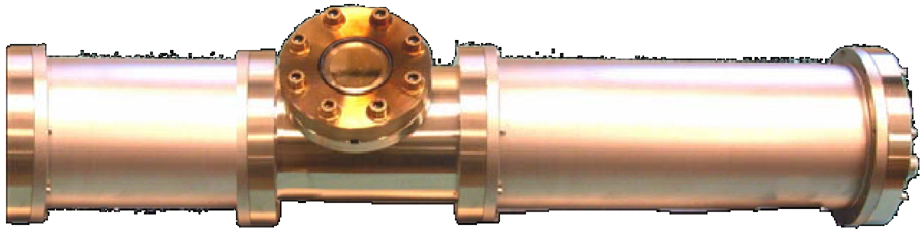
Natural source of muons from cosmic radiation
Muons when passing through material are deflected
with an angle that is proportional to Z

Placing position-sensitive detectors
(drift-chambers) below and above
the inspected object it is possible
to evidence shadows produced
by heavy materials
with image reconstruction techniques



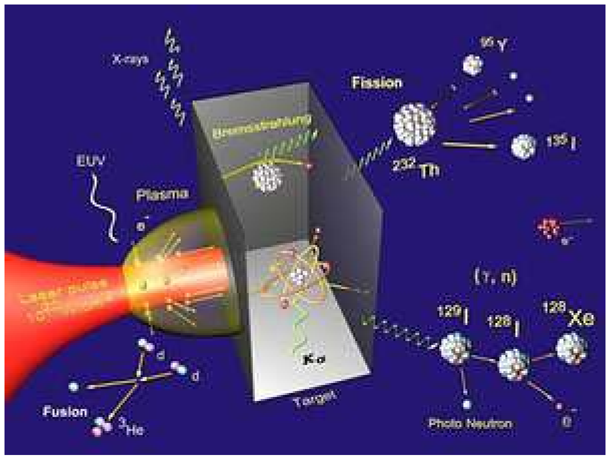
Active methods

Neutron interrogation



using (portable) generator tubes
Based on (D,T) or (D,D) reactions

Photofission



using:
- **electron accelerators + bremsstrahlung**

or
- **tabletop laser systems**

JRC
EUROPEAN COMMISSION

Portable equipment

ipsc
Institute for the Protection and Security of the Citizen

From technological point of view is OK:

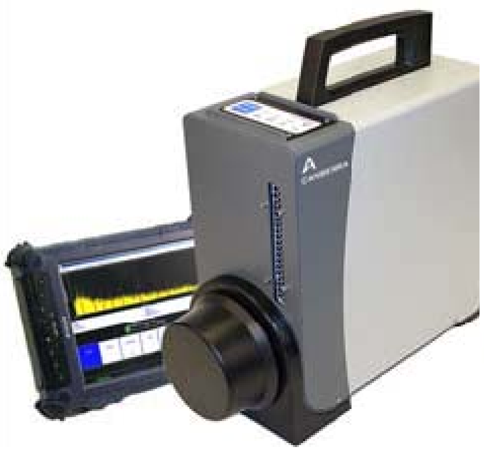
- portable radiometers,
- isotope identifiers
- high-resolution spectrometers based on TD-cooled HPGe
- personal dosimeters (pagers)

Special attention to be paid to:

- ergonomic
- portability
- user-friendliness

Instruments to be used by non-experts:

- few (no) settings
- few simple options
- fully automatic data analysis
- clear messages

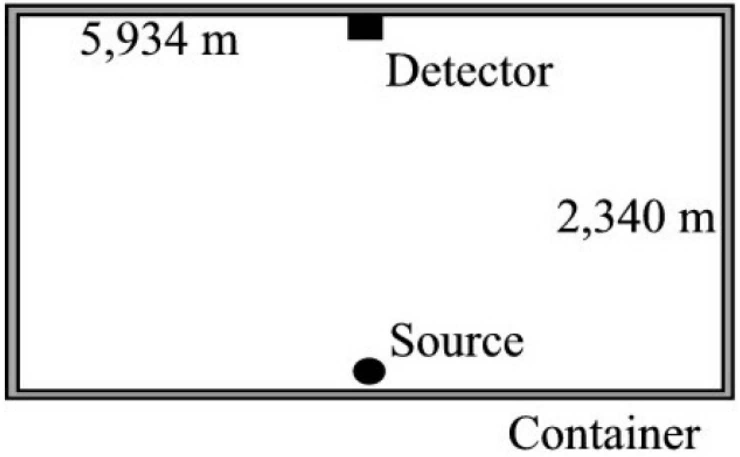


Miniaturisation

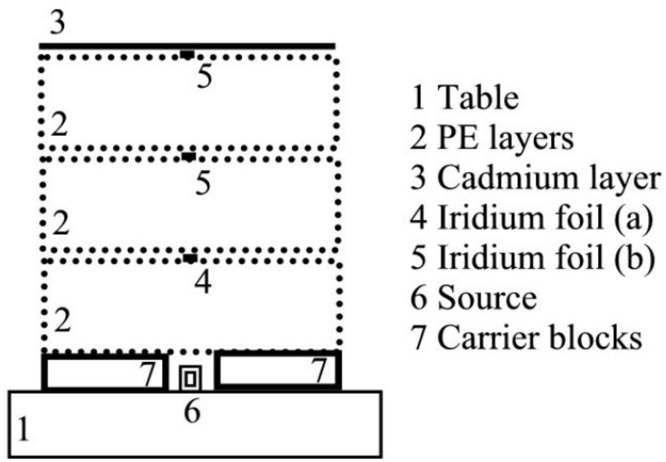
When time plays on your side!

Profit of long shipment to detect radiation through small and cheap detectors inside the shipping container:

low efficiency, but long counting time



Example: PNAA using Iridium foils
Neutrons from Pu are captured by foil
and generate Ir-192
detected by LB-gamma spectrometry



Tested at JRC experimentally and with MC
Feasibility demonstrated,
But too low activation if lot of H

The concept deserves further consideration

Conclusions

- There is no fit-all-purposes solution
  => techno-diversity
- Operational aspects have paramount importance
  lower alarm rate
  usability issues
- Combining multiple info by different sources/sensors
  smart/distributed sensors
  expert systems
- Potential novel technologies, but high-tech
  long term developments

Thank you !

For further information or questions please contact me

Email: paolo.peerani@jrc.it